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PROPORTIONAL SOLENOID-CONTROLLED FLUID VALVE HAVING
COMPACT PRESSURE-BALANCING ARMATURE-POPPET ASSEMBLY

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a continuation-in-part of
5 co-pending U.S. Patent Application, Serial No. ***, filed
***, by V. Kumar, entitled: "Proportional Solenoid-
Controlled Fluid Valve Assembly Without Non-Magnetic
Alignment Support Element" (hereinafter referred to as
the '*** application), which is a continuation-in-part of
10 co-pending U.S. Patent Application, Serial No.
09/846,425, filed May 1, 2001, by V. Kumar, (hereinafter
referred to as the '425 application), which is a
continuation of U.S. Patent application, Serial No.
09/535,757, filed March 28, 2000, now U.S. Patent No.
15 6,224,033, issued May 1, 2001 (hereinafter referred to as
the '033 Patent), which is a continuation of U.S. Patent
Application Serial No. 08/988,369, filed December 10,
1997, now U.S. Patent No. 6,047,947 (hereinafter referred
to as the '947 Patent), issued April 11, 2000, which is
20 a continuation-in-part of U.S. Patent Application Serial
No. 08/632,137, filed April 16, 1996, now U.S. Patent No.
5,785,298, issued July 28, 1998 (hereinafter referred to
as the '298 Patent), each application being assigned to
the assignee of the present application and the
25 disclosures of which are incorporated herein.

FIELD OF THE INVENTION

The present invention relates in general to solenoid-actuated fluid control valves of the type disclosed in the above-referenced applications and 5 Patents, for use in precision fluid flow regulation systems, such as those that require precise control of the rate of fluid flow, including but not limited to pneumatic and hydraulic regulation. The present invention is particularly directed to a reduced hardware complexity 10 configuration for effectively balancing inlet and outlet pressures of the fluid ports of the valve, so that valve poppet position will be defined exclusively by the solenoid, thereby ensuring precision control of fluid flow through the valve.

15 BACKGROUND OF THE INVENTION

A number of precision fluid metering applications, such as micro-pneumatic and fuel injection systems, as non-limiting examples, employ solenoid-driven actuators to control fluid flow through a fluid supply valve. 20 Optimally, fluid flow through the valve is to be maintained very closely proportional to the current applied to the solenoid. However, varying fluid pressure conditions at the valve's inlet and/or outlet ports can significantly impact the ability of the solenoid to 25 provide the precise metering control desired.

In order to deal with this problem, it is common practice to incorporate into the valve a pressure

balancing sub-assembly, such as a dual diaphragm-based pressure-balancing mechanism of the type diagrammatically shown in cross-section in Figure 1. This dual diaphragm mechanism serves to compensate or effectively 'balance' 5 out the fluid pressures at each of its inlet and outlet ports, in order that the only translation forces acting on the valve orifice-closing poppet will be those imparted by the solenoid-driven armature.

More particularly, in the valve architecture of 10 Figure 1, compensation for the pressure P_1 of a fluid applied to a valve inlet port 11 of a solenoid-operated fluid valve 10 is provided by an 'upper' diaphragm 21, installed between an armature-poppet connecting rod 23 and a solenoid actuator assembly 25. The upper end of the 15 connecting rod 23 engages the moveable armature 24 of the solenoid actuator, while the lower of the connecting rod 23 engages a poppet 27, that is sized to be closed against a valve seat 31 surrounding a valve orifice 33. The valve orifice 33 provides fluid communication between 20 a fluid cavity 35, to which fluid inlet pressure P_1 at the valve inlet port 11 is applied, and a fluid exit port 37 from which fluid at a valve outlet pressure P_2 is derived.

By making the annular area A_{D1} of the 'upper' 25 diaphragm 21 substantially the same as or very close to that of the area A_0 of the orifice 33, the downward force (as viewed in Figure 1) imparted by the inlet fluid pressure P_1 against the poppet 27 will be substantially

the same as or performance-wise sufficiently close to the 'upward' force imparted by the pressure P_1 against the upper diaphragm 21, thereby effectively neutralizing the contribution of the pressure P_1 to the position of the 5 valve poppet 27 relative to the valve seat 31.

In a complementary manner, compensation for the fluid pressure P_2 at the exit port 37 is provided by a 'lower' diaphragm 41, installed between the lower end 43 of a poppet-connecting rod 45 and the valve body 47. The 10 upper end 51 of the connecting rod 45 engages the poppet 27. Similar to the compensation mechanism for the pressure P_1 , the annular area A_{D2} of the 'lower' diaphragm 41 is made substantially the same as or very close to that of the area A_o of the orifice 33.

15 As a consequence, any upward force imparted by the pressure P_2 against the poppet 27, that might otherwise tend to lift the poppet off the valve seat 31 (and thereby undesirably render solenoid control ineffective), will be countered by 'downward' force imparted by the 20 pressure P_2 against the lower diaphragm 41, so as to effectively neutralize the contribution of the pressure P_2 to the position of the valve poppet 27 relative to valve seat 31.

Now, although a dual diaphragm-based pressure 25 compensation structure of the type shown in Figure 1 is effective for its intended purpose, it is hardware intensive in terms of the added diaphragm, connecting rods and increased sized and additional boring of the

valve body proper. This added hardware complexity not only increases the size of the assembly, but the cost and complexity of its manufacture, as well.

SUMMARY OF THE INVENTION

5 In accordance with the present invention, advantage is taken of the magnetic field coupling and fluid containment structure of the integrated ferromagnetic pole piece employed in the solenoid-operated valve described in the above-referenced '*** application, to
10 incorporate a poppet/armature bore-based, pressure-balancing scheme, that not only ensures that valve poppet position will be defined exclusively by the solenoid, but does so in a manner that allows the hardware complexity, size and cost of assembly to be significantly reduced
15 relative to the prior art, such as the dual diaphragm structure, described above.

As will be described, the pressure balanced, solenoid-controlled fluid valve assembly of the invention includes a valve unit and a solenoid-driven, valve actuator. The solenoid-driven, valve actuator unit is preferably of the type described in my above-referenced '*** application, having an integrated magnetic pole piece that provides fluid leakage containment. It also couples axial, radial and magnetic shunt flux paths with
20 a moveable armature without the need for non-magnetic material for alignment, support or magnetic flux flow path control. The valve unit is similar to the those of
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the above-referenced '425 application, and the '947 and '033 Patents, positioning a valve poppet relative to a fluid flow orifice through the valve proper.

To balance out inlet and exit port fluid pressures, 5 the valve unit incorporates a fluid flow restriction with the armature/poppet-positioning mechanism between the armature cavity and the fluid inlet cavity. In addition, the poppet and its poppet-positioning armature have an interior bore that serves as an auxiliary fluid path 10 between the fluid exit port and the armature cavity. This combination is effective to balance fluid pressures at the fluid inlet and exit ports applied to the opposite sides of the restriction, in a manner that is complementary to the fluid pressures applied to opposite 15 sides of the poppet, thereby effectively neutralizing the effects of fluid pressure on poppet position.

In a first embodiment, a poppet/armature assembly is coupled with a pressure-balancing diaphragm, that has an annular area substantially the same as or very close to 20 the area of the valve bore orifice. The diaphragm is retained by an armature support member, so as to provide a fluid seal between an upper armature cavity containing the armature, and a cavity containing the valve seat, and ported to the fluid inlet port.

25 The valve actuator unit includes a unitary pole piece having a generally axial pole piece portion, that extends into an upper solenoid/pole piece cavity coupled in fluid communication with the upper armature cavity by

way of an annular fluid gap. Fluid leakage containment for this upper cavity structure is provided by the fluid-sealing structure of the pole piece and the diaphragm. The integral pole piece and support architecture do not

5 require a non-magnetic material in the magnetic flux flow path. An axial bore in the lower end of the axial portion of the pole piece accommodates a compression spring urged against the armature and axially biases the armature, and thereby the poppet against the valve seat.

10 An auxiliary axial bore through the armature provides fluid communication between the valve bore, (which is in fluid communication with the fluid exit port, and the axial gap between the lower distal end of the axial portion of the magnetic pole piece. Since the

15 axial gap is in fluid communication with the upper (fluid leakage-contained) cavity structure that includes the upper solenoid/pole piece cavity and the armature cavity, it couples the exit port pressure to the top side of the fluid restriction diaphragm.

20 Since, the area of the fluid restriction diaphragm is substantially the same as the valve bore orifice upward force imparted against the poppet by the fluid exit port pressure is countered by a downward force at that same pressure, that has coupled through the

25 auxiliary bore to the top of the diaphragm. In a complementary manner, the pressure at the fluid inlet port is balanced as a result of a downward force imparted by the inlet fluid pressure against the poppet being

substantially the same as the upward force imparted by the pressure against the bottom of the fluid restriction diaphragm.

In a second embodiment, the fluid restriction 5 comprises an O-ring inserted into an annular groove of an armature support member. Similar to the diaphragm of the first embodiment, this O-ring has an annular area substantially the same as or very close to that of the area of the valve bore orifice. A single spiral-10 configured suspension spring supports the armature-poppet. The pressure-balancing function provided by the O-ring is similar to that of the diaphragm in the first embodiment.

Pursuant to a third embodiment, the fluid 15 restriction mechanism is implemented without a captured element; instead, the restriction is defined by the geometry of a very narrow annular aperture between the outer surface of the armature-poppet and the inner surface of an armature insertion bore through the 20 surrounding support member. The geometric parameters of the armature-poppet, including its outer diameter and auxiliary internal bore size, and those of the armature insertion bore through the support member, are such as to limit or restrict 'upward' fluid flow of the inlet 25 pressure and 'downward' fluid flow of the outlet pressure, in a manner that is proximate the force imparted by these pressures on opposite sides of the armature-poppet relative to the valve orifice. This

neutralizes the contribution of the fluid inlet and outlet pressures on the position of the armature-poppet relative to the valve seat.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Figure 1 is a longitudinal, cross-sectional diagrammatic illustration of a proportional solenoid-controlled fluid valve assembly containing a conventional dual diaphragm-based fluid pressure compensation mechanism;

10 Figure 2 is a longitudinal, cross-sectional diagrammatic illustration of a first embodiment of the improved proportional solenoid-controlled fluid valve assembly embodying the fluid pressure compensation scheme of the invention;

15 Figure 3 diagrammatically illustrates a second embodiment of the invention, in which the fluid restriction mechanism is implemented by means of an O-ring inserted into an annular groove of an armature support member; and

20 Figure 4 diagrammatically shows a third embodiment of the invention, in which the fluid restriction mechanism is implemented by a narrow annular aperture between the outer surface of the armature-poppet and the inner surface of an armature insertion bore in the

25 armature support member.

DETAILED DESCRIPTION

Attention is now directed to Figure 2, which is a longitudinal, cross-sectional diagrammatic illustration of a proportional solenoid-controlled fluid valve, having

5 a fluid pressure balancing arrangement in accordance with a first embodiment of the invention. Unless otherwise indicated or inherently apparent, the architecture of Figure 2 (as well as those of Figures 3 and 4) is cylindrically symmetrical about a longitudinal axis A.

10 As pointed out briefly above, and as will be detailed below, this arrangement employs a fluid flow restriction between the armature cavity and the fluid inlet cavity, plus a fluid communication path through the valve closing assembly between the fluid exit port and

15 the armature cavity. The combination of these two mechanisms effectively balances both the inlet and outlet forces acting upon the valve poppet, so that valve poppet position is controlled exclusively by the solenoid.

The solenoid-controlled fluid valve assembly

20 includes a valve unit 200 the fluid flow path through which is controlled by a solenoid-driven, valve actuator unit 300. The solenoid-driven, valve actuator unit 300 is preferably of the type described in my above-referenced '*** application, and employs an integrated magnetic pole

25 piece that is configured to provide fluid leakage containment, as well as axial, radial and magnetic shunt flux paths with a moveable armature that drives the valve poppet, but without the conventional need for non-

magnetic material for alignment, support or magnetic flux flow path control.

The valve unit 200 is similar to the valve units of the solenoid-controlled valve assemblies of the above-referenced '425 application, and the '947 and '033 Patents, and is operative, under solenoid-driven actuator control, to position a valve poppet relative to a fluid flow orifice through the valve proper. To balance out inlet and exit port fluid pressures, valve unit 200 incorporates a fluid flow restriction coupled to the armature/poppet-positioning mechanism between the armature cavity and the fluid inlet cavity. In addition, the poppet and its associated poppet-positioning armature are provided within an interior bore that provides a fluid communication path between the fluid exit port and the armature cavity.

As pointed out above, and as will be detailed below, this combination of the fluid flow restriction and the fluid communication path causes fluid pressures at the fluid inlet and exit ports to be applied to the opposite sides of the restriction, in a manner that is complementary to the fluid pressures applied to opposite sides of the poppet, thereby effectively neutralizing the effects of fluid pressure on poppet position.

More particularly, the valve unit 200 is shown as comprising a generally cylindrical base member 202 having a fluid input port 204 and a fluid exit port 206. Each of the fluid input and exit ports, which may be respectively

interiorly threaded, as shown at 208 and 210, respectively, so as to facilitate their being coupled to respective sections of fluid transporting conduit (not shown). Within the generally cylindrical valve base 5 member 202, the fluid exit port 206 is coupled to a first generally cylindrical interior valve bore 212 that extends to a valve orifice 214, that terminates at and is surrounded by a (generally circular) valve seat 216.

Although the valve seat 216 is shown as being fixed 10 within the body 202 of valve unit 200, it may alternatively be configured as an adjustable valve seat, such as one installed in a threaded portion of the valve bore (as shown diagrammatically in the embodiments of Figures 3 and 4, to be described). In this alternative 15 configuration, the valve seat may be maintained in a fluid sealed condition within the valve bore 212 by means of one or more (e.g., a pair of) O-rings. The orifice 214 of the valve bore 212 opens into an interior valve poppet cavity 218 in which a valve poppet 220 is retained by an 20 translatable, axially bored armature 222 for solenoid-controlled closure against and opening away from the valve seat 216. The valve poppet cavity 222 is coupled to the fluid inlet port 204 by way of a bore 224 therebetween.

25 As further shown in Figure 2, valve poppet 220 may have a generally stepped cylindrical body 226, which terminates at a lower generally circular face 228. The poppet face 228 has a depression 230, into which a fluid

5 tight sealing ring 232, such as an annular shaped neoprene ring, may be press fit. This annular sealing ring 232 is sized to cover and thereby seal the poppet 220 against the circular valve seat 216, when brought into closing contact thereagainst by the solenoid-driven armature 222.

10 The valve poppet 220 also includes an interior axial bore 234, which is sized to snugly engage and fit upon the outer cylindrical surface 236 of a lower narrow cylindrical end 238 of the axially bored armature 222. When the valve poppet 220 is affixed upon the lower cylindrical end 238 of the armature 222, it retains an interior ring portion 240 of a diaphragm 242 against the lower surface 244 of the armature 222. Like the upper 15 diaphragm 21 in the dual diaphragm structure of Figure 1, the diaphragm 242 has an annular area A_{242} that is substantially the same as or very close to that of the area A_{214} of the bore orifice 214.

20 A relatively increased thickness, generally circular circumferential portion 246 of the diaphragm 242 is captured and sealed between an interiorly projecting radial portion 248 of an inverted, generally cup-shaped armature support member 250, and a retaining ring 252 that is fit (e.g., threaded) into a generally circular 25 depression 254 of the support member 250. When so captured, the diaphragm 242 provides a fluid seal between an upper armature cavity 256 containing the armature 222

and the valve poppet cavity 218 containing the poppet 220 and the valve seat 216.

The axially translatable armature 222 has a generally annular shoulder 260 that is adapted to 5 cooperate with an associated surface 262 of the support member 250, so as to support a first spiral-configured suspension spring 264 on a first side of an inner spring-retaining, ferrule-shaped spacer 266, that is sized to fit around the outer cylindrical surface 268 of the 10 armature 222.

A second spiral-configured suspension spring 270 is captured between a second side of the inner ferrule-shaped spacer 266 and a generally cylindrically shaped armature sleeve 272, that is retained upon an upper 15 portion 274 of the armature 222. A generally outer circumferential region 276 of the second spiral suspension spring 270 is captured between a generally disc-shaped support member 278 atop the support member 250 and an interior surface portion 302 of a lower, cup-shaped portion 304 of a ferromagnetic pole piece 306 of 20 solenoid-driven, valve actuator unit 300.

As pointed out briefly above, and as will be described, the solenoid-driven, the valve actuator unit 300 is preferably configured essentially as shown and 25 detailed in the above-referenced *** application. The cup-shaped portion 304 of the pole piece 306 may threadingly engage the outer cylindrical surface 280 of support member 250, with an O-ring 282 providing a fluid

seal therebetween. The valve body 202 is sized to receive and engage a lower interior cylindrical portion 308 of the cup-shaped portion 304 of the pole piece 306.

The solenoid-driven, valve actuator unit 300 may be 5 securely attached to the valve unit 200 by way of set-screws (not shown) inserted through bores (two of which are shown at 310 and 312) in the pole piece 306, and screwed into tapped bores (not shown) in the upper surface 203 of the valve body 202. An O-ring 284 is 10 captured between a generally circular slot 286 of the lower surface 288 of the support member 250 and the valve body 202, so as to seal the support member 250 against valve body 202, and thereby provide a sealed or contained fluid flow path between the fluid inlet and exit ports 15 and the poppet cavity 218.

The axially translatable armature 222 and associated armature sleeve 274 extend through a generally cylindrical annular bore 314 formed by a radially inward projecting portion 316 of magnetic pole piece 306 (that 20 is solid with the cup-shaped portion 304 thereof). As a result, an outer cylindrical surface 290 of armature sleeve 274 is slightly radially spaced apart from the interior cylindrical surface 318 of radially inward projection 316 of the pole piece and forms a narrow 25 annular fluid (air) gap 320 therebetween.

The generally cylindrical annular bore 314 opens into a upper solenoid/pole piece cavity 341, that is bounded by a relatively thin portion 342 of a generally

annular sleeve pole piece portion 340 of the magnetic pole piece 306. This upper cavity 341 is coupled in fluid communication with the upper armature cavity 256 by way of the annular air gap 320. As will be described, fluid 5 leakage containment for this upper cavity structure is provided by the fluid-sealing integrated structure of the pole piece 306, on the one hand, and the diaphragm 242, on the other hand. (As noted earlier, the diaphragm 242 provides a fluid seal between an upper armature cavity 10 256 containing armature 222 and the valve poppet cavity 218, in which the poppet 220 and the valve seat 216 are disposed.)

Because the annular air gap 320 is very narrow and of a fixed radial distance, the magnetic flux path 15 between the armature 222 and the radially inward projecting portion 316 of the magnetic pole piece 306 is a low magnetic reluctance radial path. Thus, as in the patented architectures, referenced above, the substantial reluctance of the axial air gap 336 between 20 the moveable armature 222 and the distal end of the generally axial portion 322 of the magnetic pole piece, in combination with the relatively low magnetic reluctance in the radial direction across the radial air gaps, effectively by-passes the axial air gap and 25 confines the magnetic flux in radial air gap regions.

The armature 222 terminates at a generally planar, circular top surface 294 adjacent to a generally axial or longitudinal portion 322 of the magnetic pole piece 306.

The generally axial portion 322 of the magnetic pole piece 306 is configured of a generally cylindrical solid ferromagnetic element, that is generally coaxial with the axis A and is sized to fit within the generally 5 cylindrical bore 324 of a solenoid coil 326. As shown, the solenoid coil may be installed within a housing 328 of ferromagnetic material. The housing 328 may be provided with a sidewall aperture or bore 329 for electrical leads 332 that supply electrical connection 10 between the solenoid coil and a current control source (not shown).

The generally axial portion 322 of the magnetic pole piece 306 has a lower distal end 334 that is axially spaced apart from and magnetically coupled with the top 15 generally circular surface 294 of axially translatable armature 222, so as to form an axial air gap 335 therebetween. An axial bore 323 formed in the lower end of the axial portion 322 of the pole piece 306 receives a compression spring 325 that is urged against the top 20 surface 294 of the axially translatable armature 222, and serves to axially bias the armature 222 and its associated poppet 220 downwardly so that the poppet is urged against the valve seat 216.

Extending axially outwardly from the distal end 334 25 of the generally axial portion 322 of the magnetic pole piece 306 is a generally tubular or ferrule-shaped projection 336, having a tapered or varying thickness in the axial direction. This tapered ferrule-shaped

projection 336 is radially spaced apart from and magnetically coupled with outer cylindrical surface 290 of the armature sleeve 274 of the armature 222, by a radial air gap 338 therebetween, so as to form a magnetic flux path shunt.

Alternatively, in lieu of providing the annular shunt projection 336 on the distal end of the generally axial portion 322 of magnetic pole piece 306, an equivalent shunt structure may be provided by configuring the top generally circular surface circular surface 294 of the armature 222 with a tapered annular projection, that is spaced apart from and magnetically coupled with the distal end 334 of the generally axial portion 322 of the magnetic pole piece 306. In either case, the ferrule-shaped projection allows for relative axial translation between the movable armature 222 and the magnetic pole piece 306, as the moveable armature 222 is axially translated.

The magnetic pole piece 306 further includes generally annular sleeve pole piece portion 340 that is continuous with the first, generally axial portion 322 and includes relatively thin portion 342 that is radially spaced apart from the lower end of the pole piece portion 322, and becomes rapidly saturated by the magnetic field generated by the solenoid coil 326. To provide for fluid leakage containment, the annular sleeve pole piece portion 340 is made effectively mechanically solid with the main pole piece portion 322.

In the embodiment of Figure 2, this is accomplished by configuring the first, generally axial portion 322 of the pole piece 306 as a generally cylindrical component and externally threaded as shown at 344, so that it may 5 be threaded into a threaded interior cylindrical bore 346 of the annular sleeve portion 340 of the pole piece 306. A fluid seal is provided by means of an O-ring 348 captured within an annular groove 350 formed within the cylindrical sidewall of axial pole piece portion 322. In 10 an alternative configuration, the main and annular pole piece portions may be formed of the same magnetic pole piece element, so as to obviate the need for an O-ring.

The relatively thin segment 342 of the annular pole piece portion 340 extends to and is solid with the 15 radially inward projecting portion 316 of the pole piece 306. For mechanical alignment, the cylindrical shape of the radial air gap 320 constrains movement of the armature 222 in the axial direction only. This serves to prevent potential off-axis distortion of the suspension 20 springs 264 and 270, so that proper operation of the valve is not impaired. Axial alignment is reinforced by the fact that the radial air gap 320 is radially aligned with and axially offset from the shunt radial air gap 338, thereby providing a pair of axially displaced 25 coaxial guide air-bushings that prevent off-axis play between the moveable armature 222 and the fixed magnetic pole piece 306.

However, as described in the *** application, unlike conventional solenoid structures, the integral pole piece and support architecture does not require a non-magnetic material in the magnetic flux flow path.

5 This reduces manufacturing and hardware complexity and cost associated with solenoid structures having non-ferromagnetic materials as part of flux path containment and pole piece - armature alignment.

As pointed out briefly above, the fluid pressure
10 balancing mechanism of the invention takes advantage of this fluid leakage containment functionality of the integrated magnetic pole piece 306, by incorporating an additional fluid flow restriction mechanism between the armature cavity 256 and the fluid inlet cavity 218, and
15 providing an auxiliary fluid communication path between the armature cavity 256 and fluid exit port 206. In order to realize a compact structure, this auxiliary communication path is readily implemented without the need for any additional components, such as the
20 connecting rod and additional diaphragm components employed in the assembly of Figure 1, described above.

Instead, as shown in Figure 2, an auxiliary axial bore 223 is formed through the armature 222, so as to provide fluid communication between the valve bore 212
25 (which is in fluid communication with the fluid exit port 206) and the axial air gap 335 between the lower distal end 334 of the axial portion 322 of the magnetic pole piece 306. Since the axial air gap 335 is in fluid

communication with the upper (fluid leakage-contained) cavity structure that includes the cavity 341 and armature cavity 256, it couples the pressure P2 supplied via the auxiliary bore 223 from the fluid exit port 206 5 to the top side of fluid restriction (diaphragm) 242.

As described above, the fluid restricting diaphragm 242 has an annular area A_{242} that is substantially the same as or very close to that of the area A_{214} of the orifice 10 214 of bore 212. As a result, any upward force imparted by the pressure P2 at the fluid exit port 206 against the bottom face 228 of the poppet 220 will be countered by 15 'downward' force imparted by the pressure P2, that has coupled through the auxiliary bore to the top of the diaphragm 242. This serves to effectively neutralize the contribution of the pressure P2 to the position of the 20 valve poppet 220 relative to valve seat 216.

In a complementary fashion, the pressure P1 at the fluid inlet port 204 is balanced as a result of a downward force (as viewed in Figure 2) imparted by the 25 inlet fluid pressure P1 against the poppet 220 being substantially the same as the 'upward' force imparted by the pressure P1 against the bottom of diaphragm 242.

Figure 3 diagrammatically illustrates a second embodiment of the invention, in which the fluid restriction mechanism is implemented by means of an O-ring 360 inserted into an annular groove 362 of an armature support member 364. Similar to the diaphragm 242 of the embodiment of Figure 2, O-ring 360 has an annular

area A_{360} that is substantially the same as or very close to that of the area A_{371} of an orifice 371 of a valve bore 370.

In this embodiment, and also that of Figure 4, to be 5 described, the armature/poppet assembly is shown as being configured as a single integrated armature/poppet element 366. This armature/poppet element 366 contains an auxiliary axial bore 368, that provides fluid communication between valve bore 370 and the axial air 10 gap 335 between the lower distal end 334 of the axial portion 322 of the magnetic pole piece 306.

Moreover, as described above, in the embodiments of Figures 3 and Figure 4, a valve seat 376 is shown as having the above-described alternative adjustable 15 configuration, being installed in a threaded portion 372 of a valve seat installation bore 374 in the valve body. The valve seat 376 is maintained in a fluid sealed condition within the valve installation bore 374 by a pair of O-rings 378 and 380.

20 Also, a single spiral-configured suspension spring 382 is used to support the armature-poppet element 366. In the embodiment of Figure 3, the suspension spring 382 is held against an armature sleeve 384 by a retention washer 386. A generally outer circumferential region 388 25 of suspension spring 382 is captured between support member 364 and an interior ledge surface portion 390 of the cup-shaped portion 304 of the ferromagnetic pole piece 306.

The pressure-balancing function provided by the O-ring 360 in the embodiment of Figure 3 is similar to that of the diaphragm 242 in the embodiment of Figure 2, in that an upward force imparted by the pressure P2 at the 5 fluid exit port against the bottom of the armature-poppet 366 will be countered by 'downward' force imparted by the pressure P2, that has coupled through the auxiliary bore 368 to the top of the O-ring 360. Also, the pressure P1 at the fluid inlet port 204 is balanced as a result of a 10 downward force imparted by the inlet fluid pressure P1 against armature-poppet 366 being substantially the same as the 'upward' force imparted by the pressure P1 against the bottom of the O-ring 360.

Figure 4 diagrammatically illustrates a third 15 embodiment of the invention, in which the fluid restriction mechanism is implemented without a captured element, such as the diaphragm 242 in the embodiment of Figure 2 or the O-ring 360 in the embodiment of Figure 3. Instead, the restriction is defined by the geometry of a 20 very narrow annular aperture 400, that is formed between the outer cylindrical surface 402 of the armature-poppet 366 and the inner cylindrical surface 404 of an armature insertion bore 405 through the surrounding support member 364.

25 In this embodiment, the geometric parameters of the armature-poppet 366 (including its outer diameter and auxiliary internal bore size), and those of the armature insertion bore 405 through the support member 364, are

defined such as to limit or restrict 'upward' fluid flow therethrough of the inlet pressure P_1 and 'downward' fluid flow therethrough of the outlet pressure P_2 , in a manner that is proximate the force imparted by these 5 pressures on opposite sides of the armature-poppet 366 relative to the valve orifice 371. Again, the net result is to neutralize the contribution of each of the fluid inlet and outlet pressures P_1 and P_2 on the position of the armature-poppet relative to the valve seat.

10 As will be appreciated from the foregoing description, the solenoid-actuated valve assembly of the invention not only effectively balances inlet and outlet pressures of the fluid ports of the valve, but is implemented with reduced hardware complexity. The 15 incorporation of a fluid flow restriction between the armature cavity and the fluid inlet cavity, plus a fluid communication path through the valve closing assembly, provides a highly integrated structure that reduces overall size and cost of assembly.

20 While I have shown and described several embodiments in accordance with the present invention, it is to be understood that the same is not limited thereto but is susceptible to numerous changes and modifications as known to a person skilled in the art, and I therefore do 25 not wish to be limited to the details shown and described herein but intend to cover all such changes and modifications as are obvious to one of ordinary skill in the art.